Recent Progress on Laser-Plasma Acceleration at kHz repetition rate

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Motivations

kHz lasers → kHz secondary electron source

With current kHz lasers : tens of mJ energy

- "Low energy", 1-20 MeV adapted to some applications
- Few femtosecond duration / jitter free with respect to laser

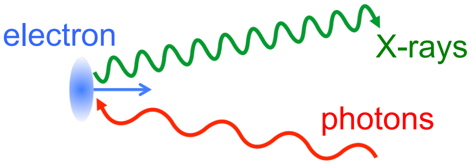
→ few femtosecond resolution in pump-probe experiments

- Compact system (turn key ?) + high repetition rate

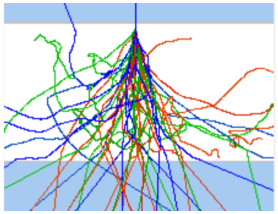
→ stability, averaging, statistics, active feedback loops

Motivations: making a LWFA at kHz

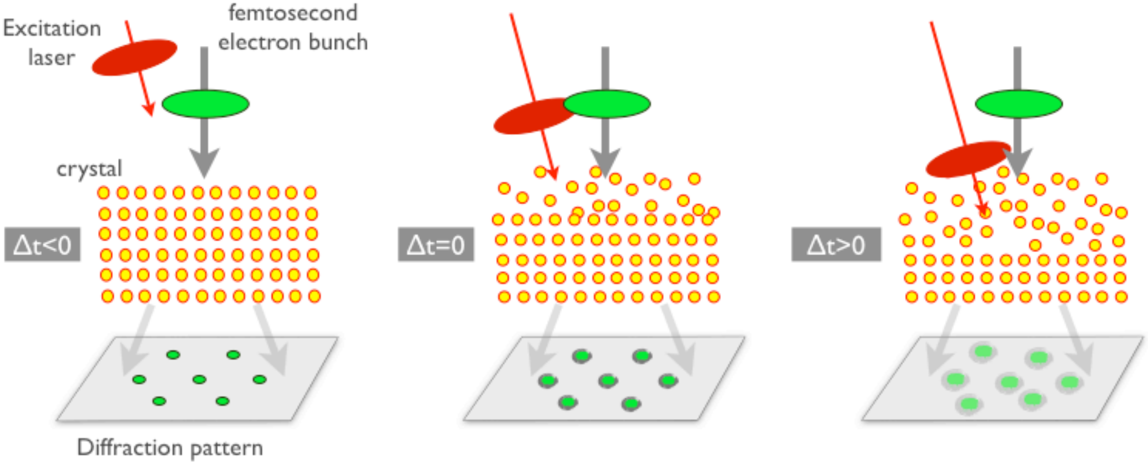
- **Electrons for driving a fs X-ray source @ kHz:**
  20 MeV electrons → 10 keV X-ray via Compton scatt.
  for fs diffraction, fs absorption (Ta Phuoc, Nat. Phot. 2012)



- **Electrons as a pump** for femtosecond irradiation:
  pulsed radiolysis (Muroya, Rad. Phys. Chem. 2008)
  radiation hardness studies (Hidding et al., Sci. Rep. 2017)



- **Electrons as a probe:** ultrafast electron diffraction for watching atomic motion in real time in complex materials
  (Mourou & Williamson, APL 41, 44 (1982), Miller, Science 343, 1108 (2014))



Outline of the talk

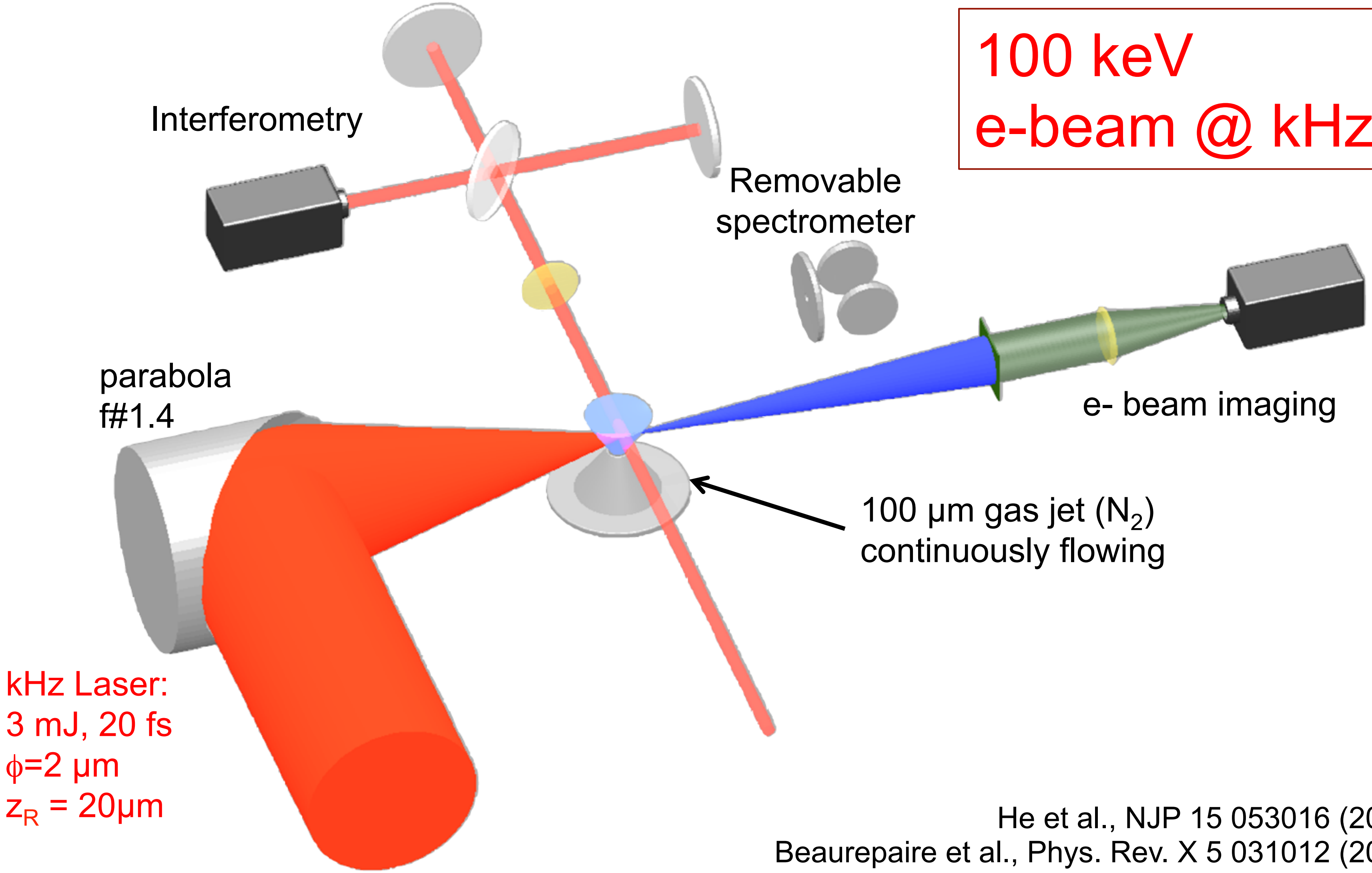
- **Review of experimental results at kHz**

- Physics of few cycle laser pulses
    - Carrier envelope phase effects
    - Dispersion effects

First results at kHz in non resonant condition

Michigan: 35 fs, 8 mJ, I=3×10^{18} W/cm^2, 500 Hz
LOA: 20 fs, 3 mJ, I=3×10^{18} W/cm^2, 1 kHz

100 keV
e-beam @ kHz



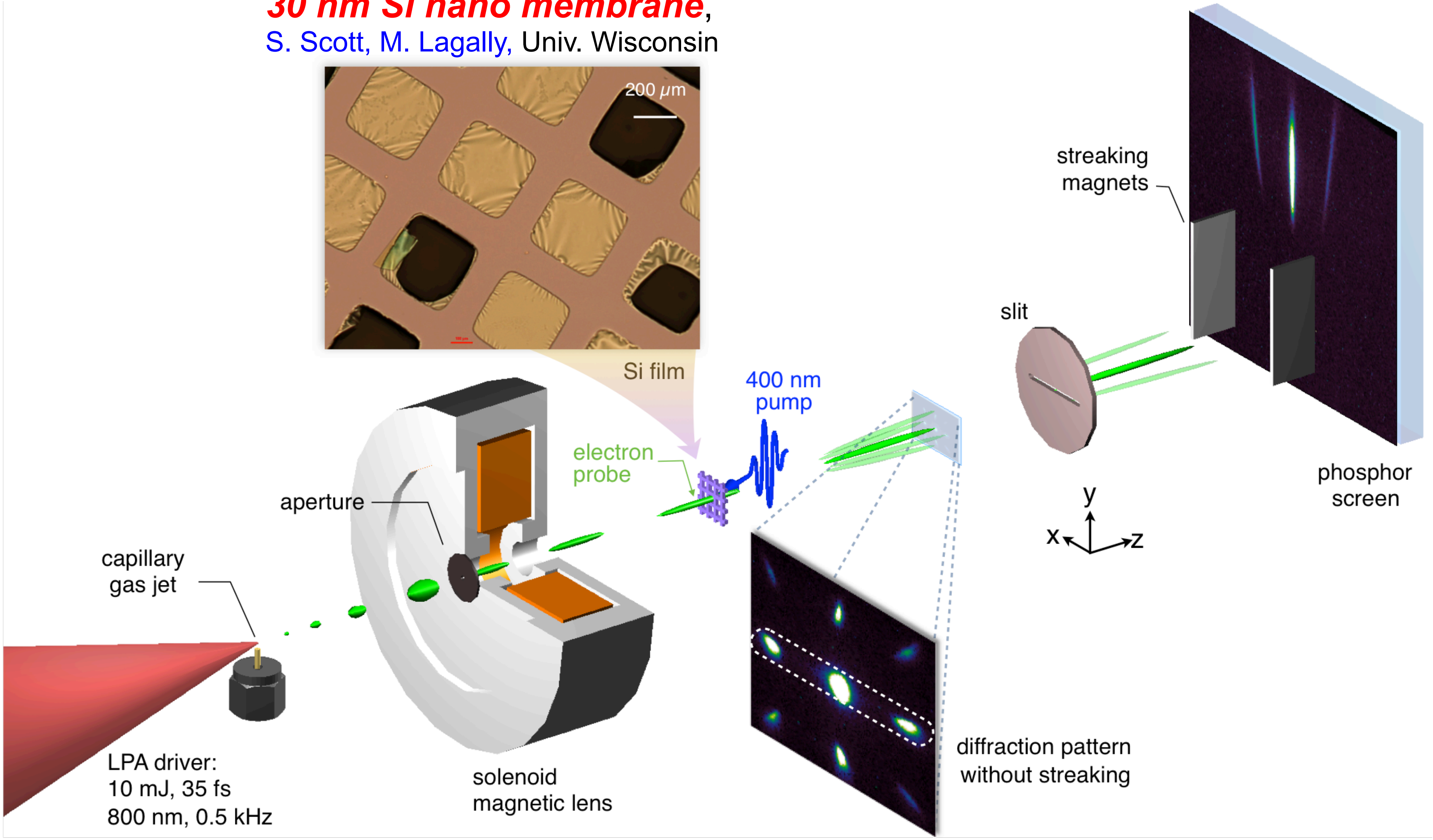
He et al., NJP 15 053016 (2013)
Beaurepaire et al., Phys. Rev. X 5 031012 (2015)

Time-resolved diffraction experiment

With 100 keV electrons

MichiganEngineering

30 nm Si nano membrane,
S. Scott, M. Lagally, Univ. Wisconsin



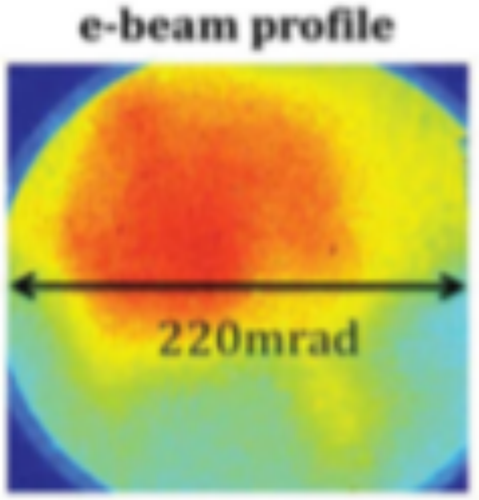
Z. He, B. Beaurepaire et al., Sci. Rep. **6**, 36224 (2016)

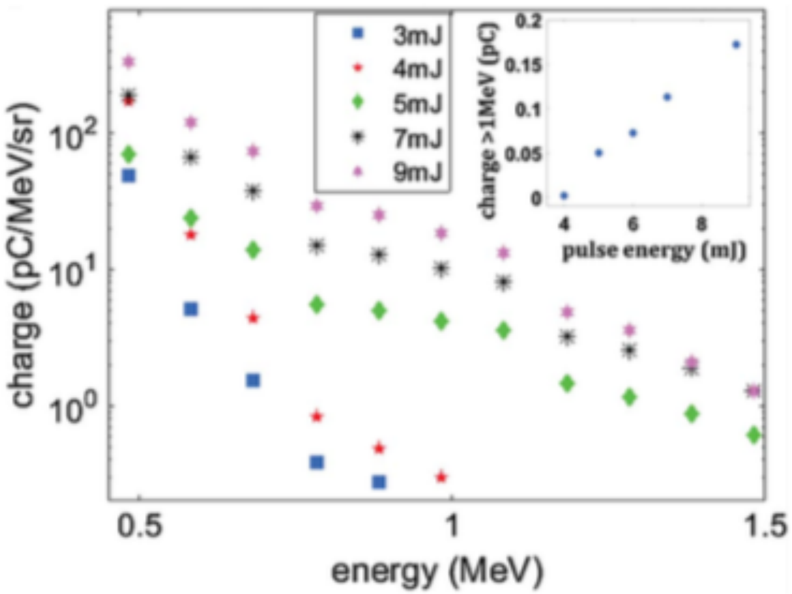
Maryland 2017: Salehi et al., OL **42** 215 (2017)

Laser: ~10 mJ , 30 fs @ 1 kHz
cooled gas jets: high density n_e=4x10^{20}- 8x10^{20}cm^{-3}

High density required for self-focusing

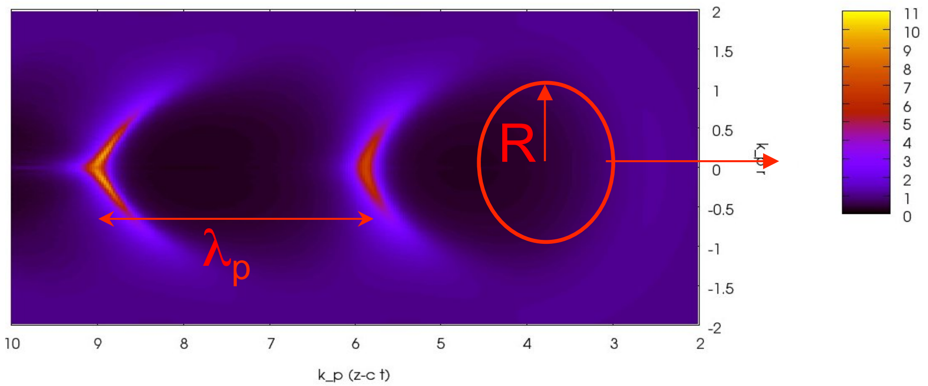
$$P_c[GW] = 17.4\frac{n_c}{n_e}$$





MeV electrons, broad angular and spectral distributions

Scaling laws toward kHz lasers: resonance condition



Laser pulse has to be resonant with plasma wave: $R \approx \lambda_p/2$, $c\tau \approx \lambda_p/2$

Laser energy scaling $E_L \propto \tau^3 \propto \lambda_p^3$ Electron energy gain $\Delta E \propto \tau^2 \propto \lambda_p^2$

30 fs → 1 J → 100 MeV-1 GeV
3 fs → mJ → 1-10 MeV

and high density $n_e > 10^{20}$ cm^{-3}

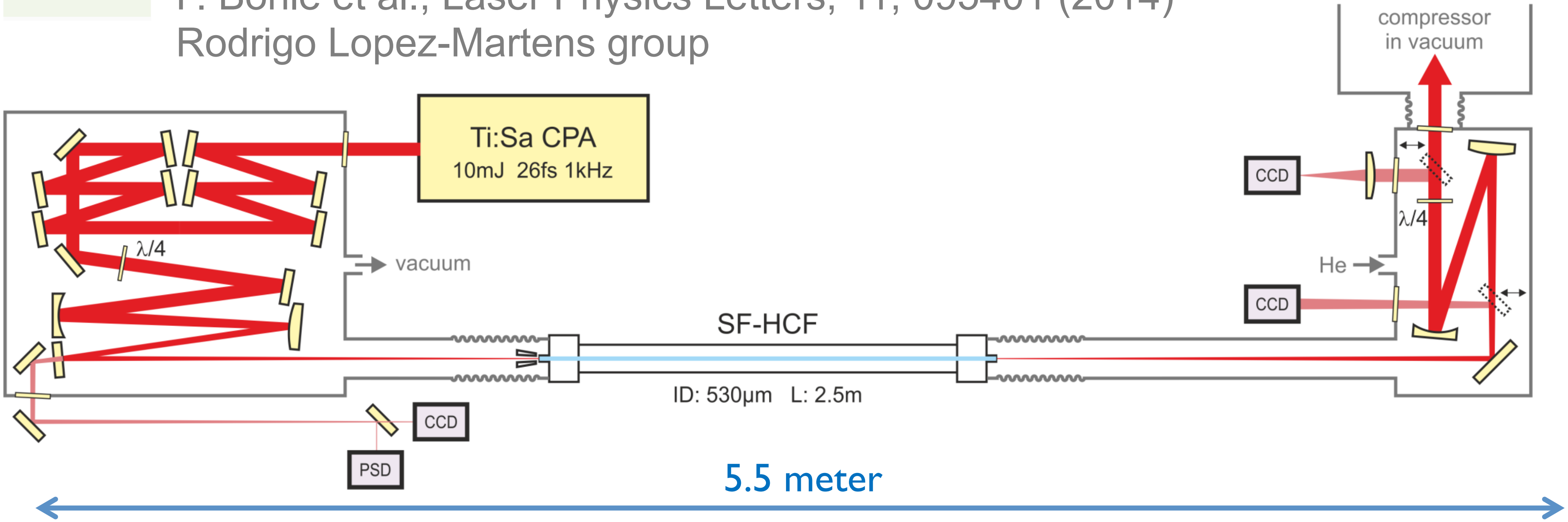
Laser pulses of 5 fs, few mJ → possible @ kHz !

Lu *et al.*, PRSTAB **10**, 0613001 (2007)

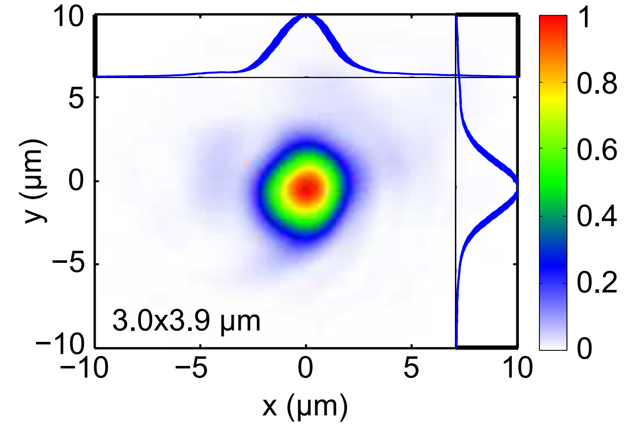
Beaurepaire et al., NJP **16**, 023023 (2014)

1 TeraWatt few-cycle kHz laser system

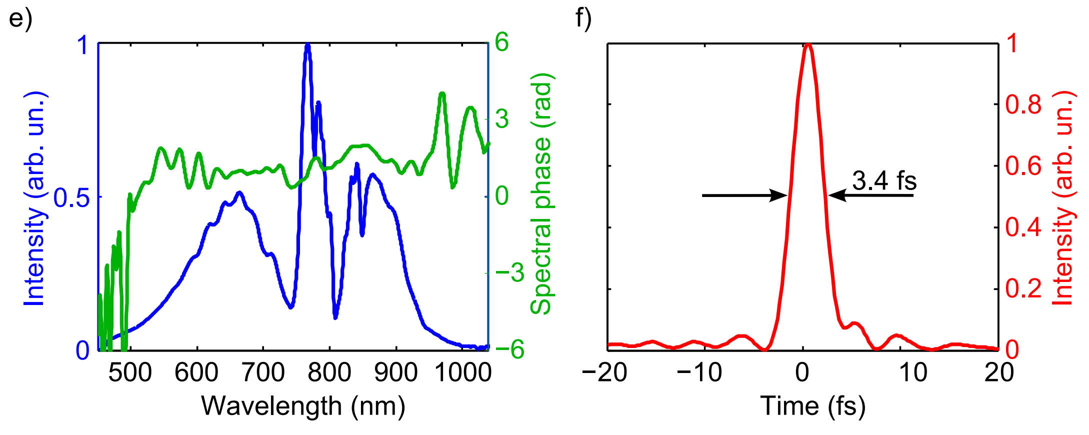
F. Böhle et al., Laser Physics Letters, 11, 095401 (2014)
Rodrigo Lopez-Martens group



a) 3 mJ, focused to 3 µm



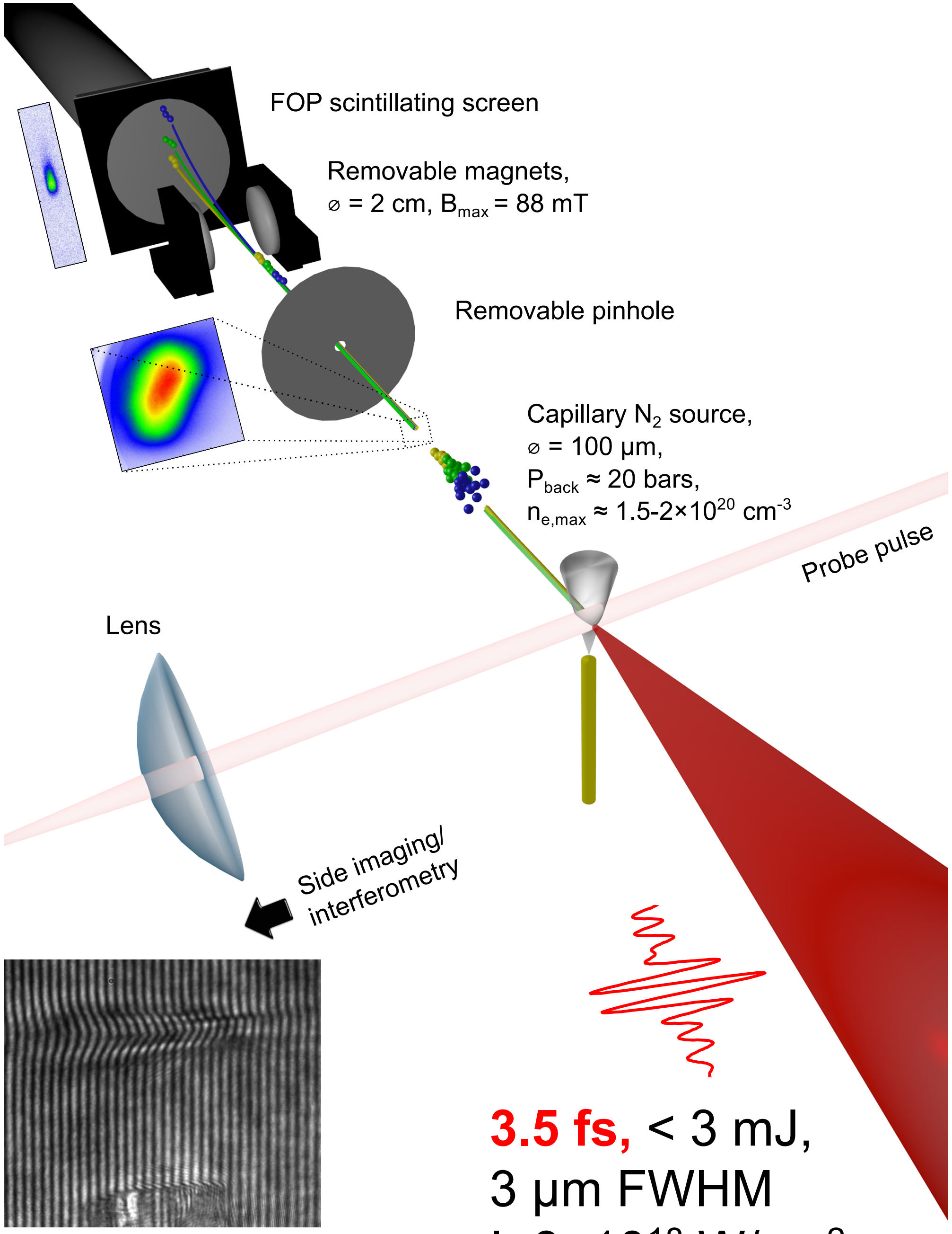
3.5-fs ~ single cycle pulse



Experimental set-up

Gas target is a continuously flowing capillary N_2 gas jet

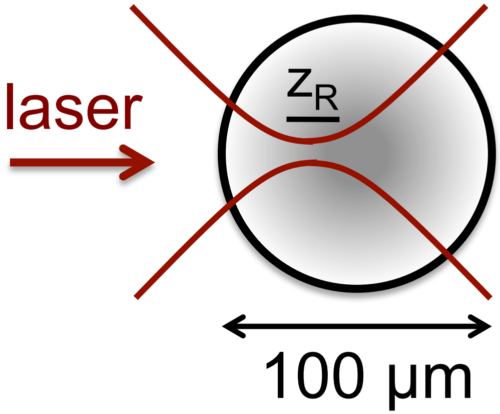
→ kHz operation !



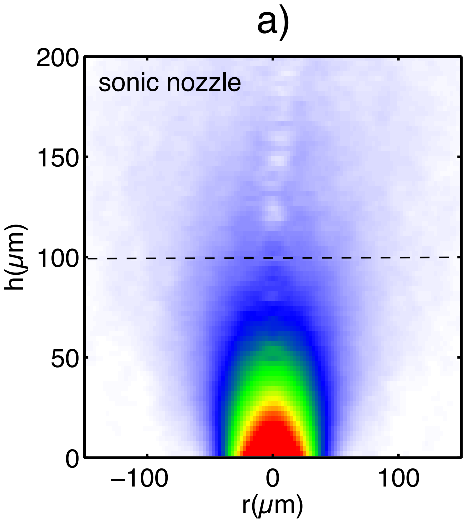
3.5 fs, < 3 mJ,
3 µm FWHM
$I = 3 \times 10^{18}$ W/cm^2

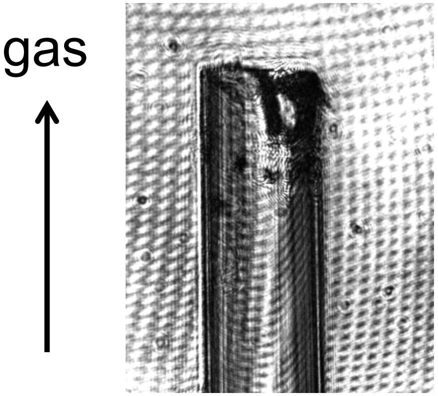
Microscale gas jets

Microscale accelerator



Rayleigh length: 20 µm
Acceleration length: 20 µm





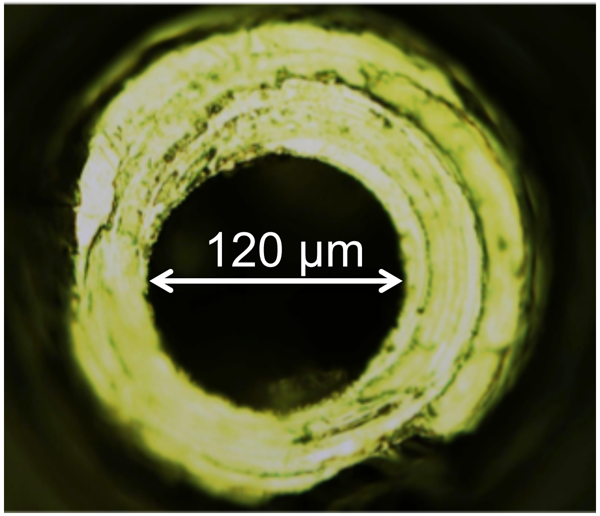
Glass capillary

Supersonic jet

D. Gustas et al., PRAB 21, 013401 (2018)

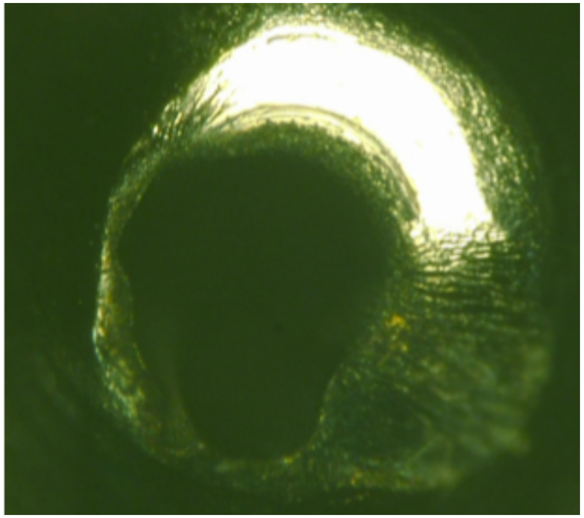
The challenge of microjets for kHz LWFA

Before experiment



Top view of jet

After 7 days, 4-6 hours/day @ kHz



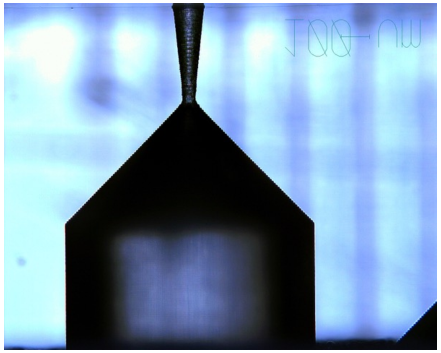
Damaged orifice

Next: dielectric jets for higher resistance

FLICE: fs laser irradiation and chemical etching

Vidmantas Tomkus group
ICPT, Lithuania

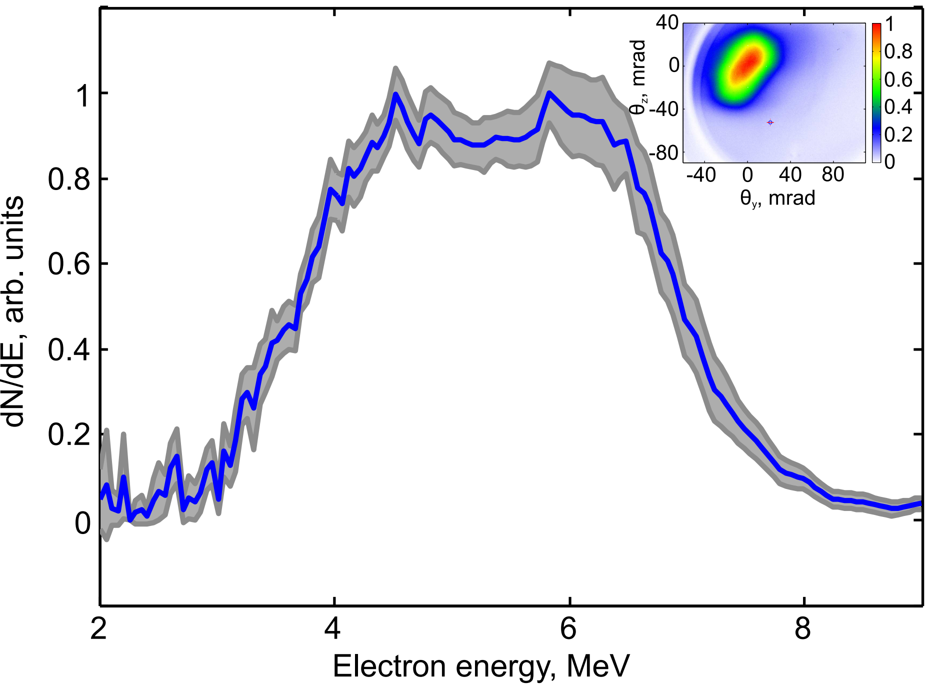
side view of jet



MeV beams at kHz repetition rate

With subsonic jet

n_e=1-2x10^{20} cm^{-3}, I=3x10^{18} W/cm^2

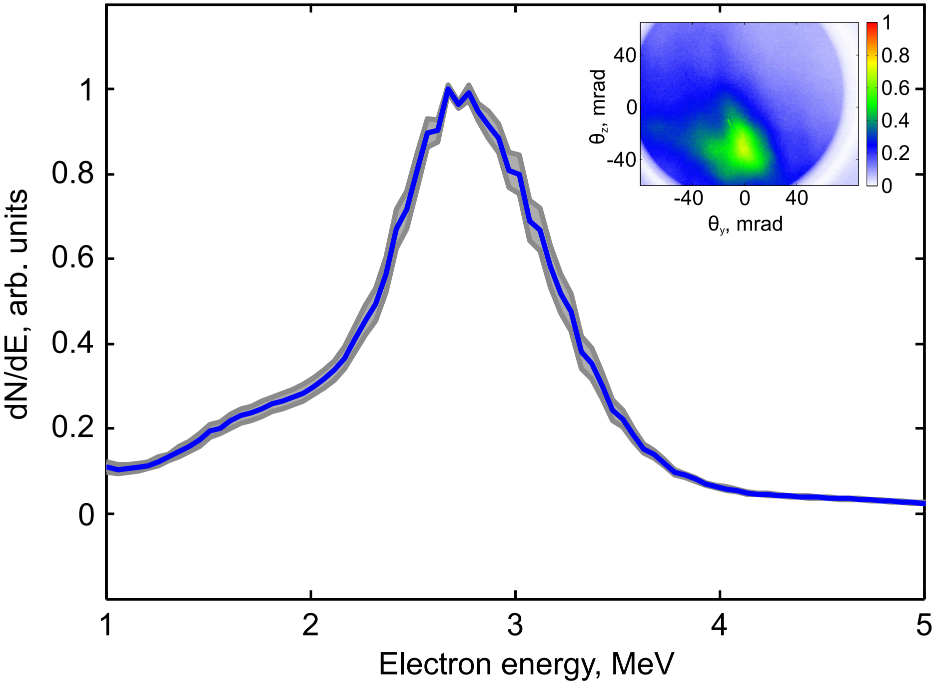


~40 mrad divergence
~100 fC, 30% rms fluc

Guénot et al., Nat. Phot. **11**, 293 (2017)

With supersonic jet

n_e=1-2x10^{20} cm^{-3}, I=5x10^{18} W/cm^2



100 times more charge
~20 pC, 10% rms fluc

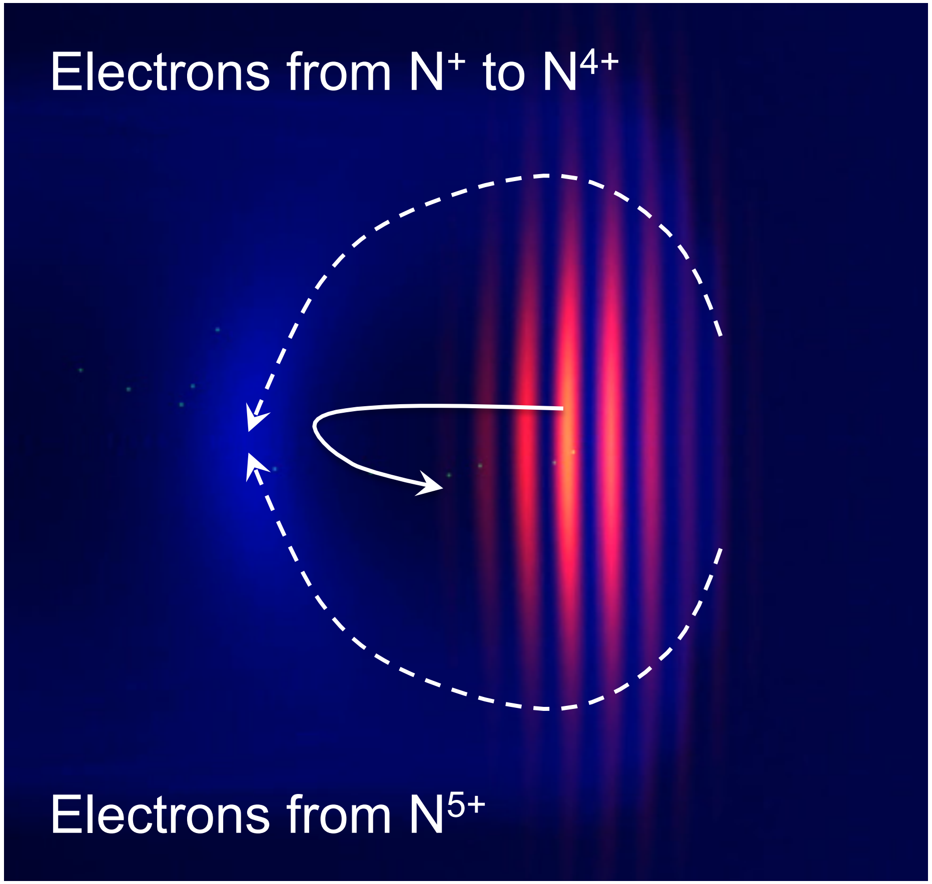
D. Gustas et al., PRAB 21, 013401 (2018)

Ionization induced injection

N^{+}	N^{1+}	N^{2+}	N^{3+}	N^{4+}	N^{5+}
14.5eV	29.5eV	47.7eV	77.2eV	97.8eV	551eV

I>10^{18} W/cm^{2} : beam electrons
→ injection

I<10^{16} W/cm^{2} : plasma electrons

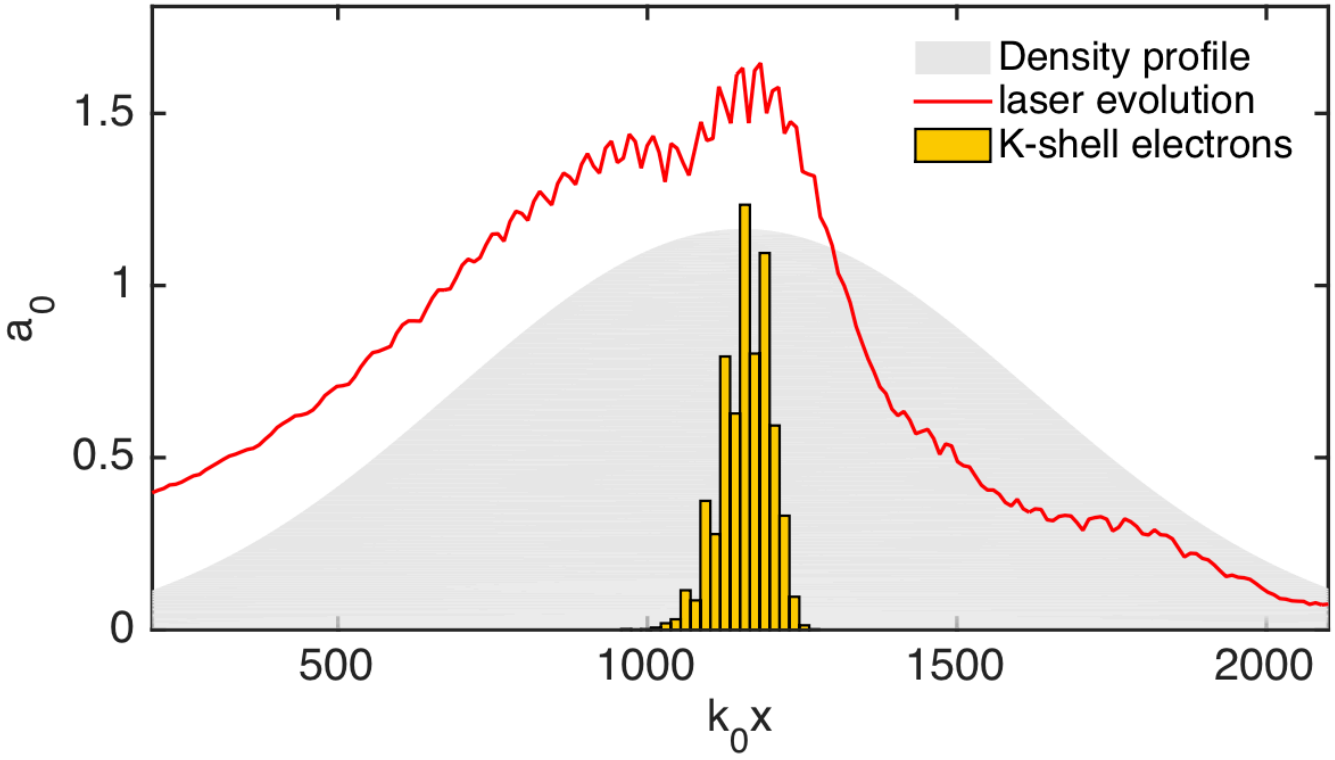


The most intense half cycles:
- ionize N^{5+}
- inject a sub-fs bunch
- depends on CEP

PIC simulations for subsonic jet case → localized ionization injection

Accelerated electrons originate from the K-shell

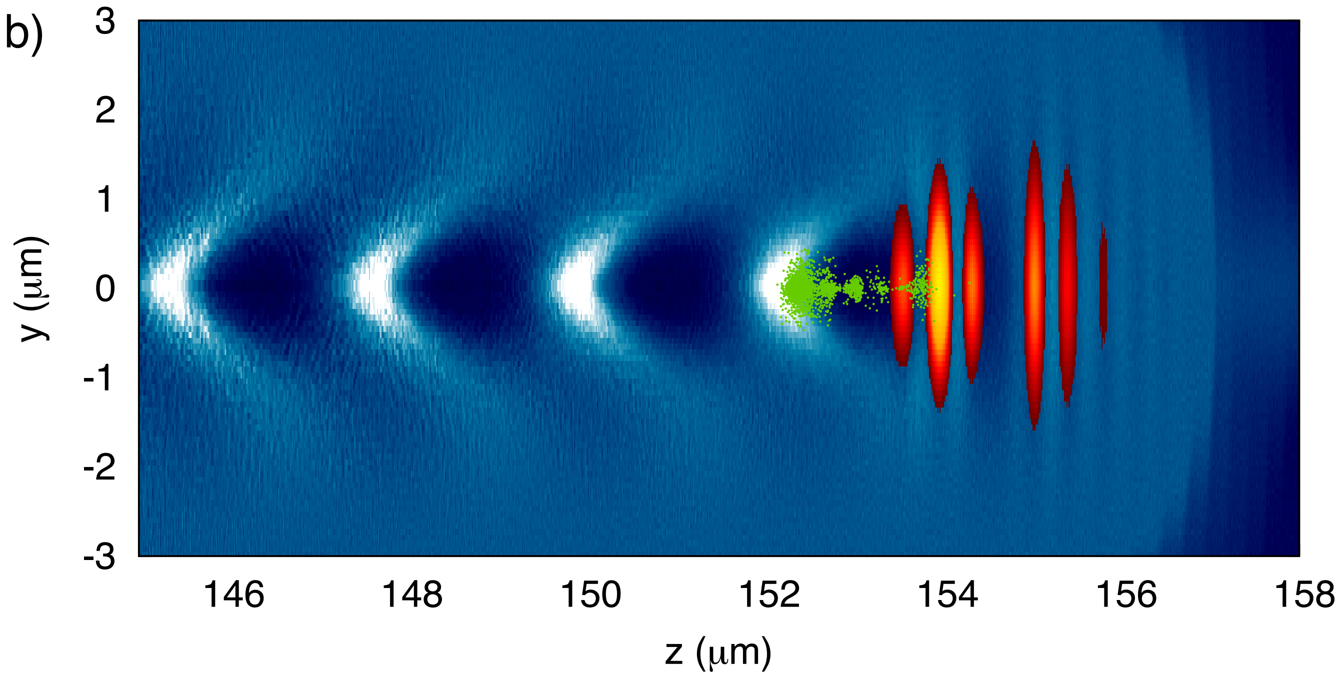
Injection length $L_{inj} < 10\ \mu m$



Guénot et al., Nat. Phot. **11**, 293 (2017), Faure et al., PPCF 2018

PIC simulations → 1 fs electron beams !

Trapped electrons in non linear wakefield



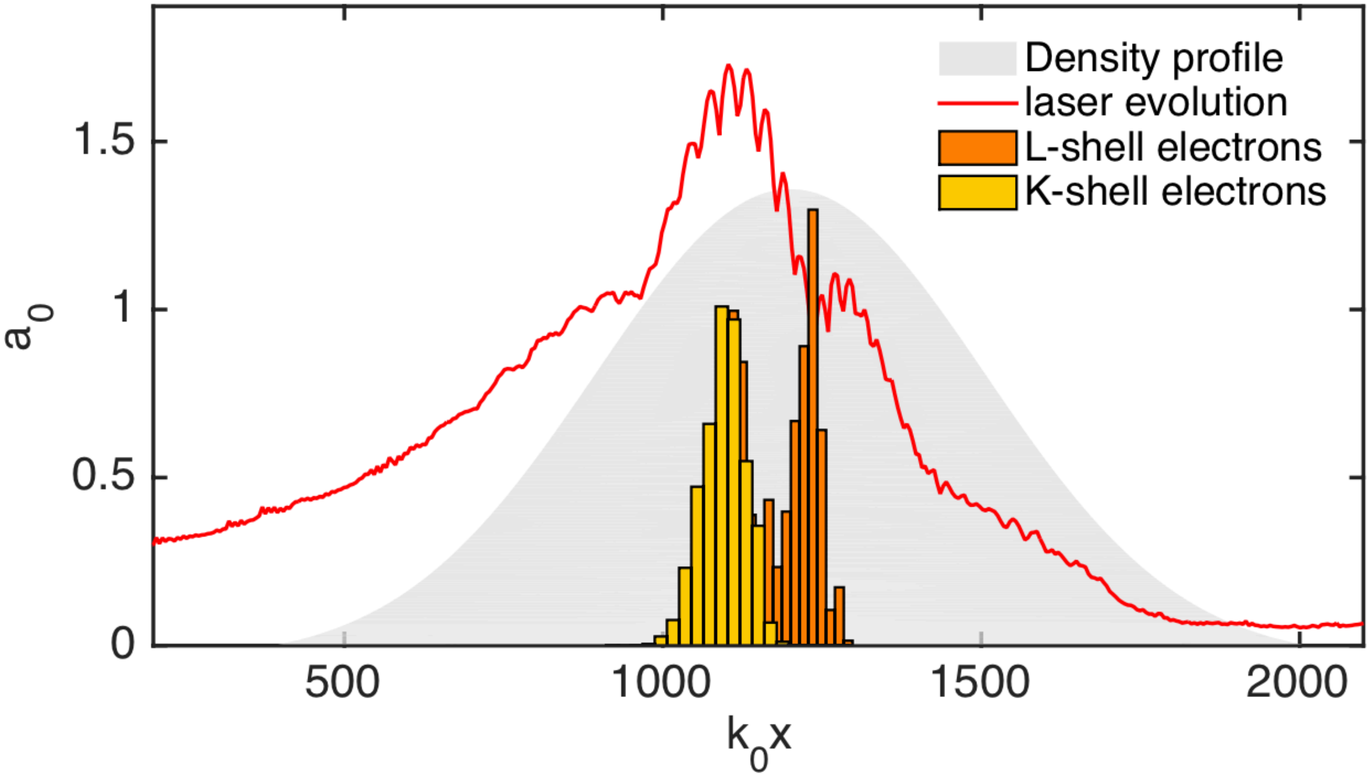
Simulation results
at the jet exit:

5 MeV beams
~ pC of charge
20 mrad divergence
1 fs duration

Guénot et al., Nat. Phot. **11**, 293 (2017)

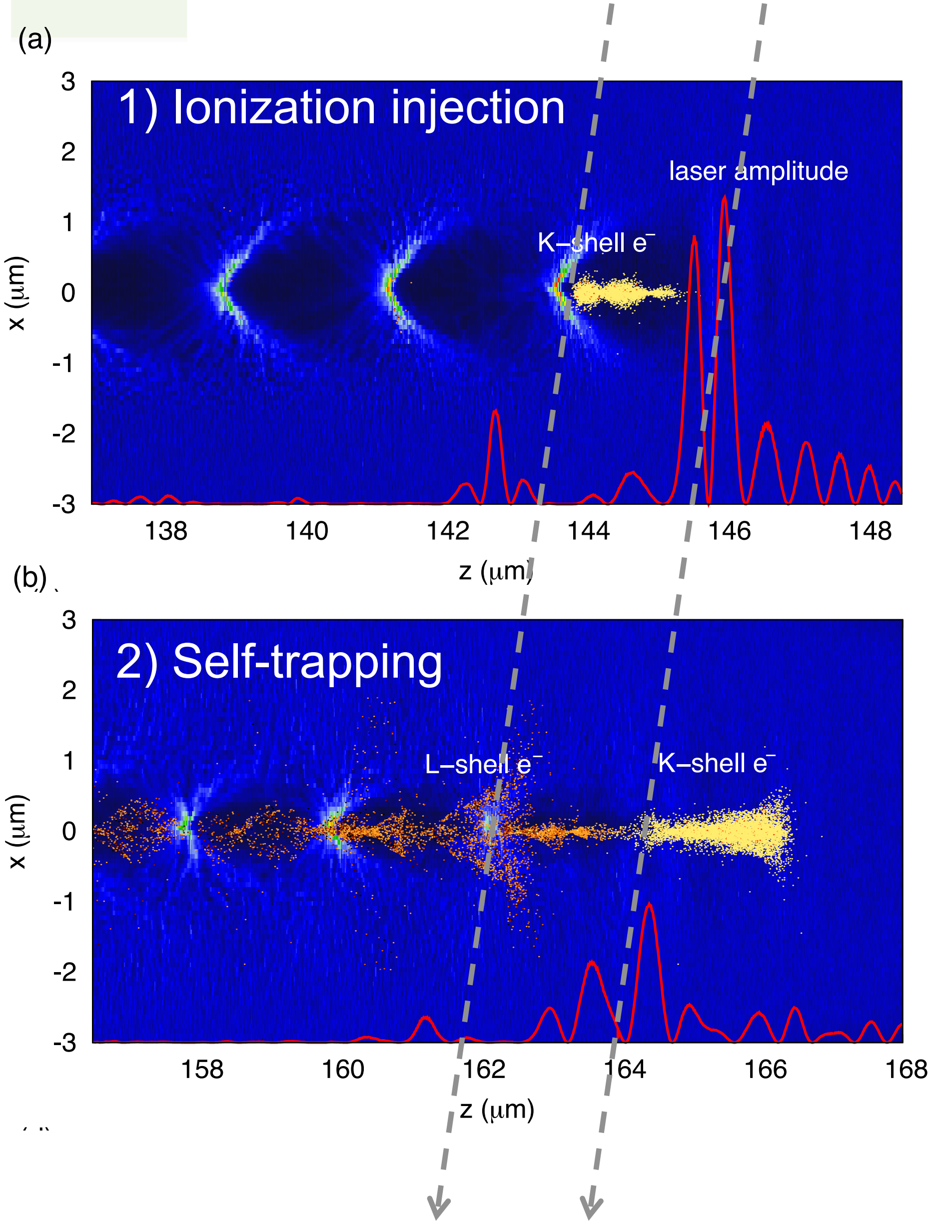
PIC simulations for supersonic jet case → 2 injection mechanisms

Ionization injection is followed by a second injection event
Less localized than before: Injection length $L_{inj} > 20$ µm



D. Gustas et al., PRAB 21, 013401 (2018). J. Faure et al., PPCF 2018

High charge due to second injection process



Red shift of the laser causes

→ Slower group velocity

→ Slower wakefield

→ Trapping of N^{3+}, N^{4+} electrons

→ Filling up of several plasma buckets: longer electron bunches

Beaurepaire et al., NJP **16** 023023 (2014)

Summary of acceleration mechanisms

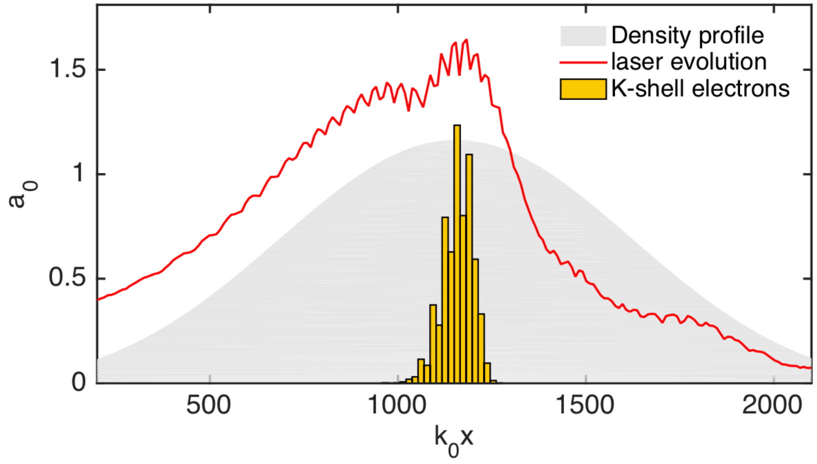
Subsonic jet

$I=3\times10^{18}$ W/cm^2

Local injection

$L_{inj} < 10$ µm

~6 MeV, < pC charge



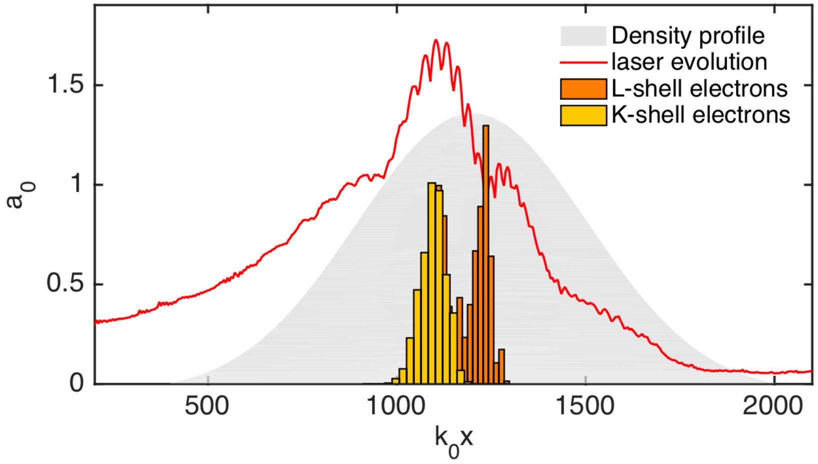
Supersonic jet

$I=5\times10^{18}$ W/cm^2

Non local injection

$L_{inj} > 20$ µm

~3 MeV, >10 pC charge



Outline of the talk

- Review of experimental results at kHz

- Physics of few cycle laser pulses
  - **Carrier envelope phase effects**
  - Effect of the number of cycles

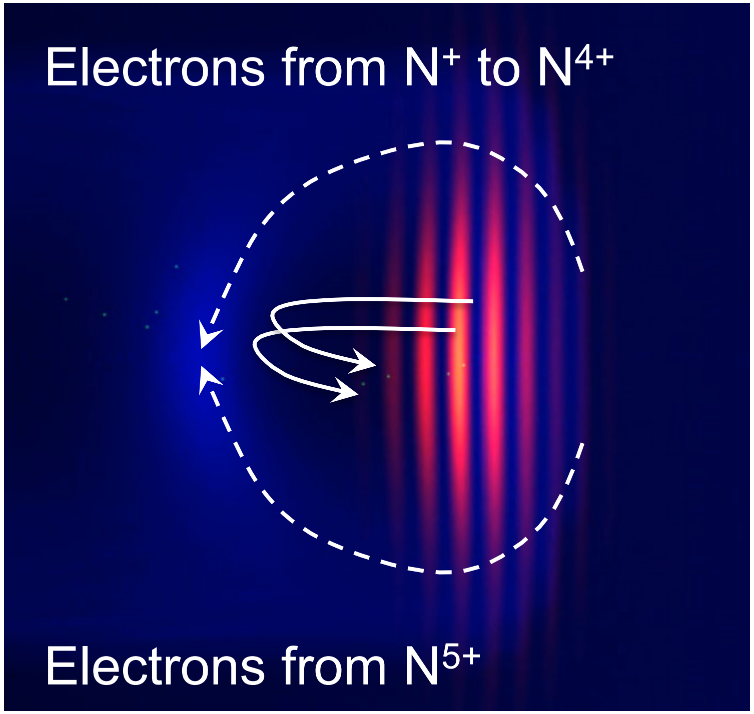
Work in progress

Expected effect of CEP on acceleration

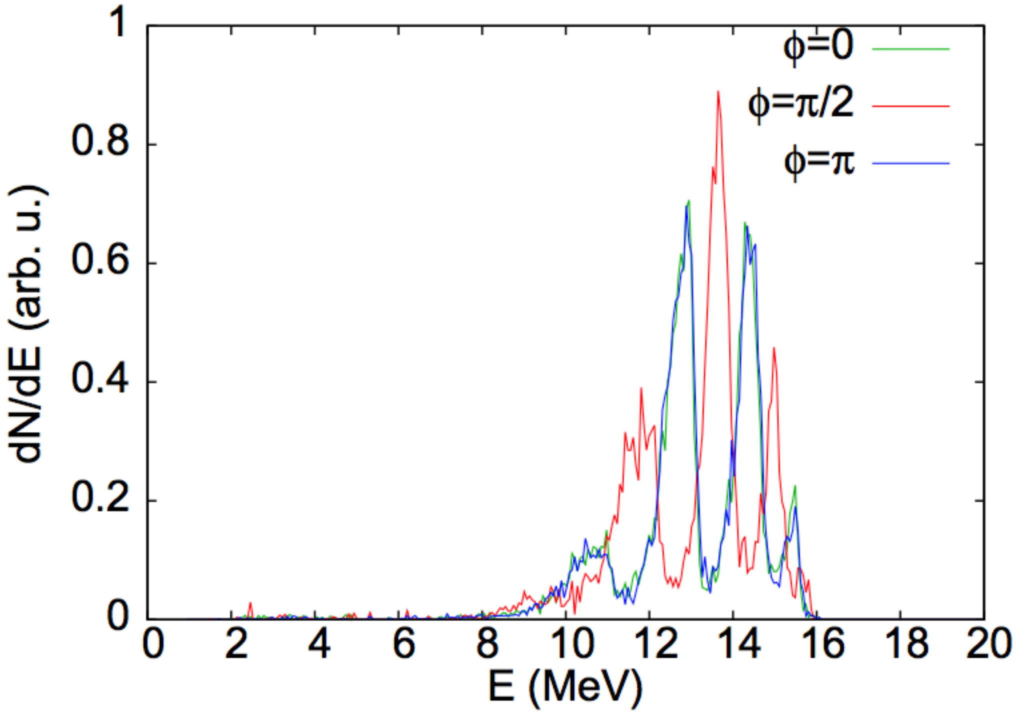
Lifschitz & Malka, NJP 14 053045 (2012)

Calder-Circ PIC simulations

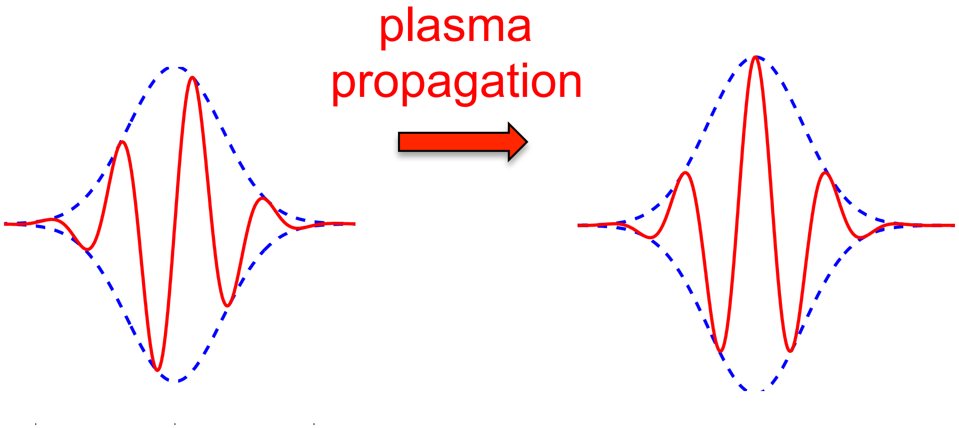
Injection depends on CEP



electron spectra (3D PIC)



CEP phase slippage



CEP slips because in the plasma

$$v_\varphi > v_g$$

The CEP slips by 2π after propagation by the ***phase slippage length***

$$L_{2\pi} = \lambda_0 \frac{c}{v_\varphi - v_g} \simeq \lambda_0 \frac{n_c}{n_e}$$

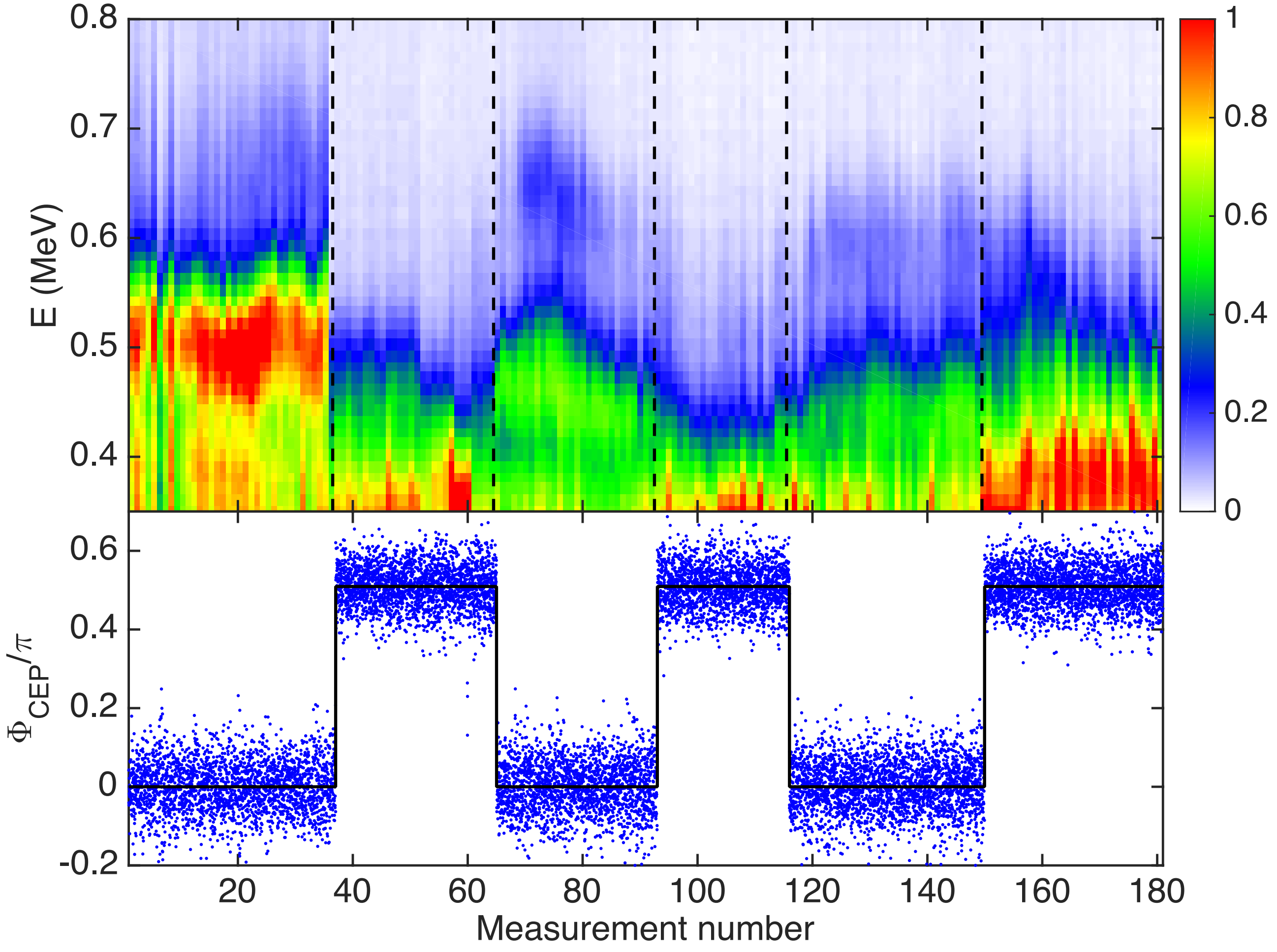
Large effects if ***injection length*** is smaller than ***phase slippage length***

$$L_{inj} \leq L_{2\pi} \simeq 10 \mu m$$

Can only be observed in the case of localized ionization injection

First clear evidence of the effect of CEP

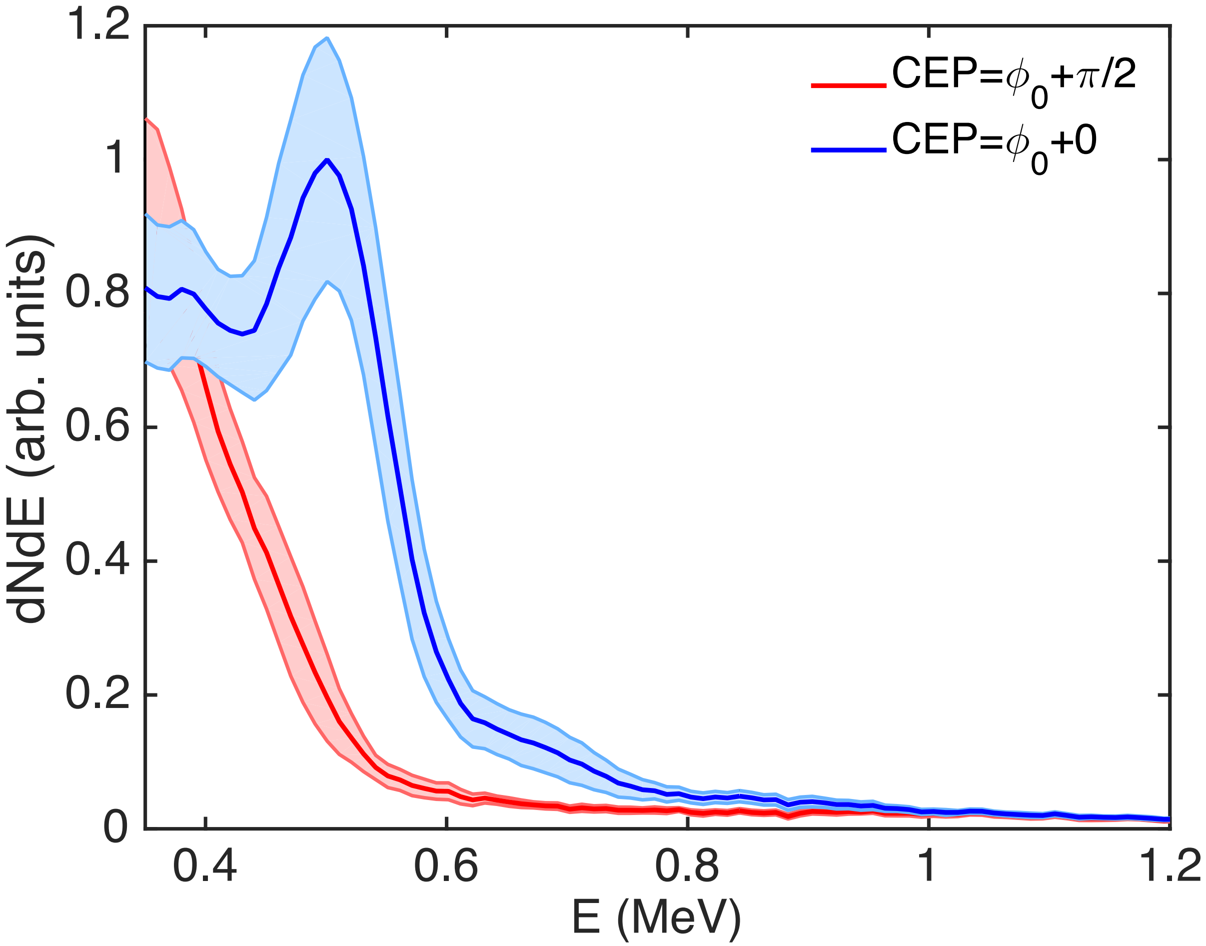
Clear evidence of CEP effect on cycling from 0 to π/2



J. Faure et al., PPCF 2018

Effect of CEP

Averaged spectra (over 40,000 shots)



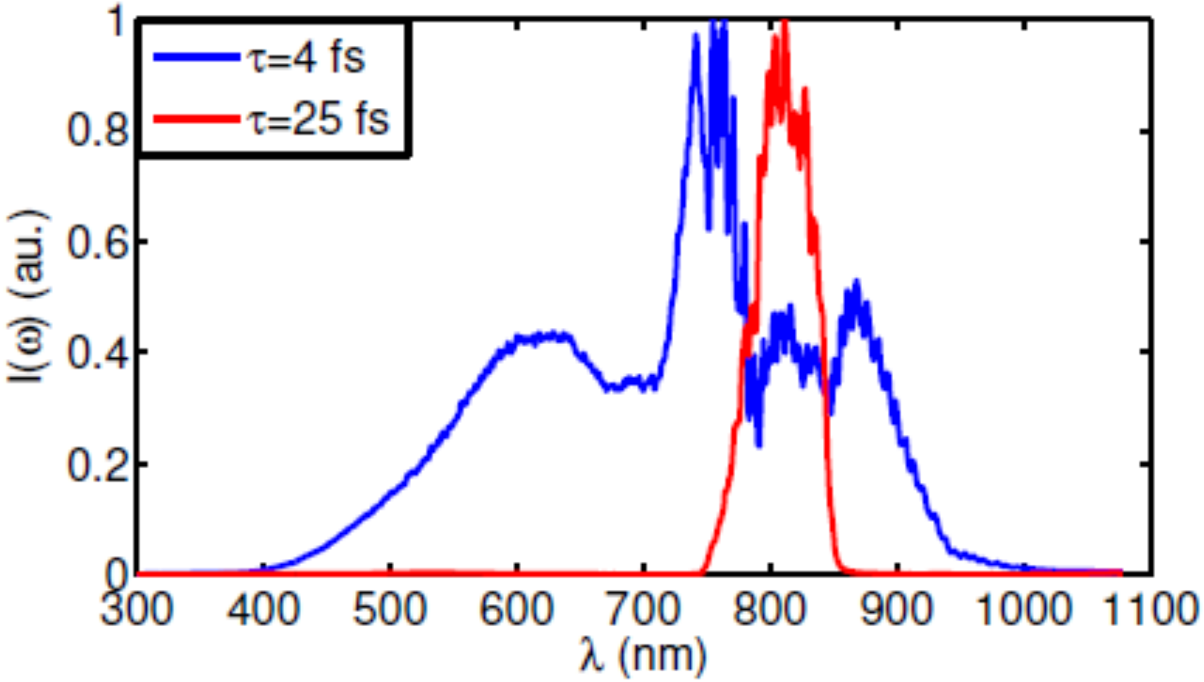
Outline of the talk

- Review of experimental results at kHz
- Physics of few cycle laser pulses
  - Carrier envelope phase effects
  - **Effect of the number of cycles**

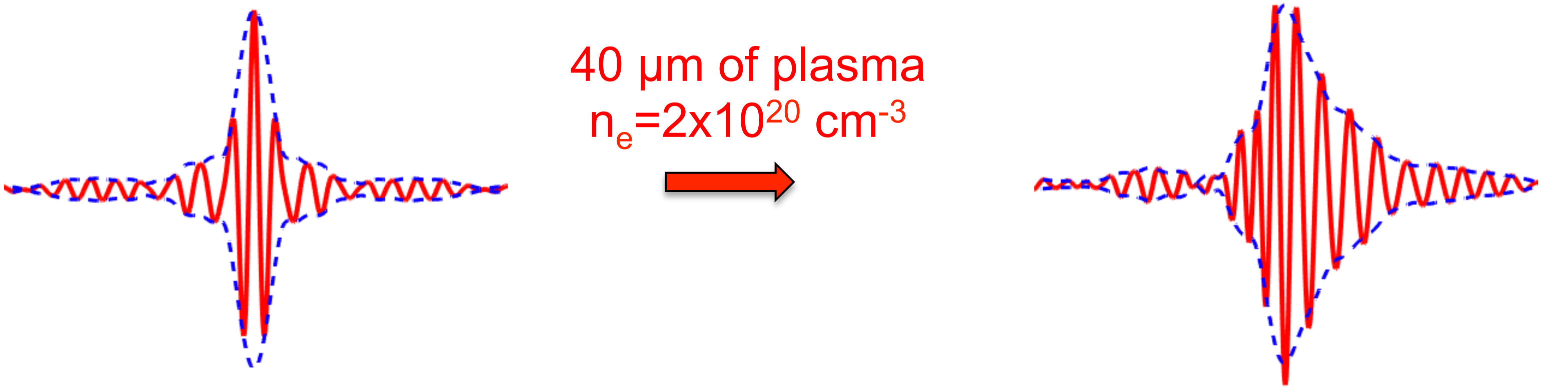
Work in progress

Spectral width and group velocity dispersion

Group velocity dispersion cannot be neglected for single-cycle pulses:



Group velocity dispersion in the plasma



40 μm of plasma
$n_e = 2 \times 10^{20}\ \mathrm{cm}^{-3}$

dispersion length

$$L_{disp} = \frac{c\omega_0}{2\Delta\omega^2}\frac{n_c}{n_e}$$

$\Delta\omega$ is the spectral width

$$L_{disp} \simeq 20\ \mu m$$

For 3.5 fs pulses

Dispersion can be mitigated by using a narrower spectrum

$$L_{disp} \simeq 100\ \mu m$$

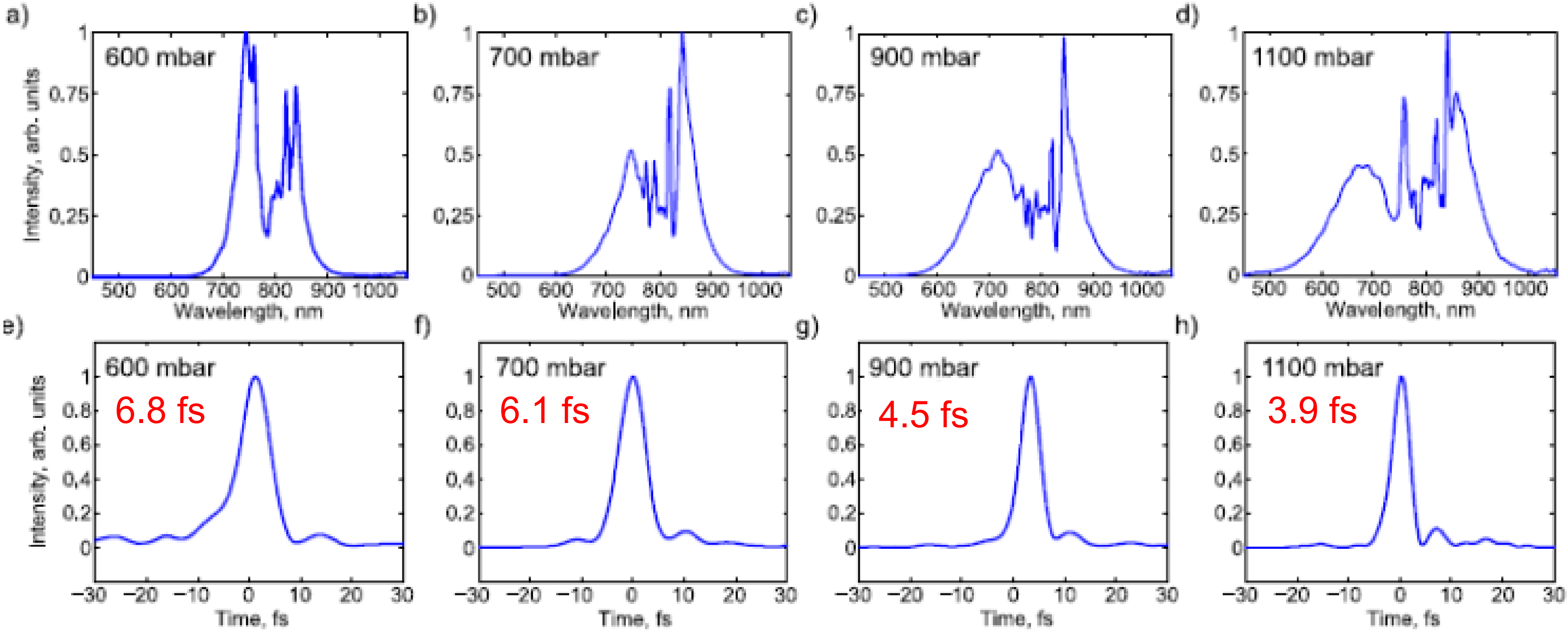
For 7 fs pulses

Mitigating dispersion with narrower spectrum

Spectrum and transform limited duration can be changed with the pressure in the hollow core fiber

$L_{disp} \simeq 100\mu m$

$L_{disp} \simeq 30\mu m$



6.8 fs

6.1 fs

4.5 fs

3.9 fs

$1.2\text{x}10^{18}$ W/cm^2

$1.6\text{x}10^{18}$ W/cm^2

$2.1\text{x}10^{18}$ W/cm^2

$2.3\text{x}10^{18}$ W/cm^2

Influence of the FTL pulse duration

Electron density (cm^{-3})

$4.2x10^{19}$ $8.8x10^{19}$ $1.8x10^{20}$ $2.6x10^{20}$ $3.5x10^{20}$

Transform limit duration

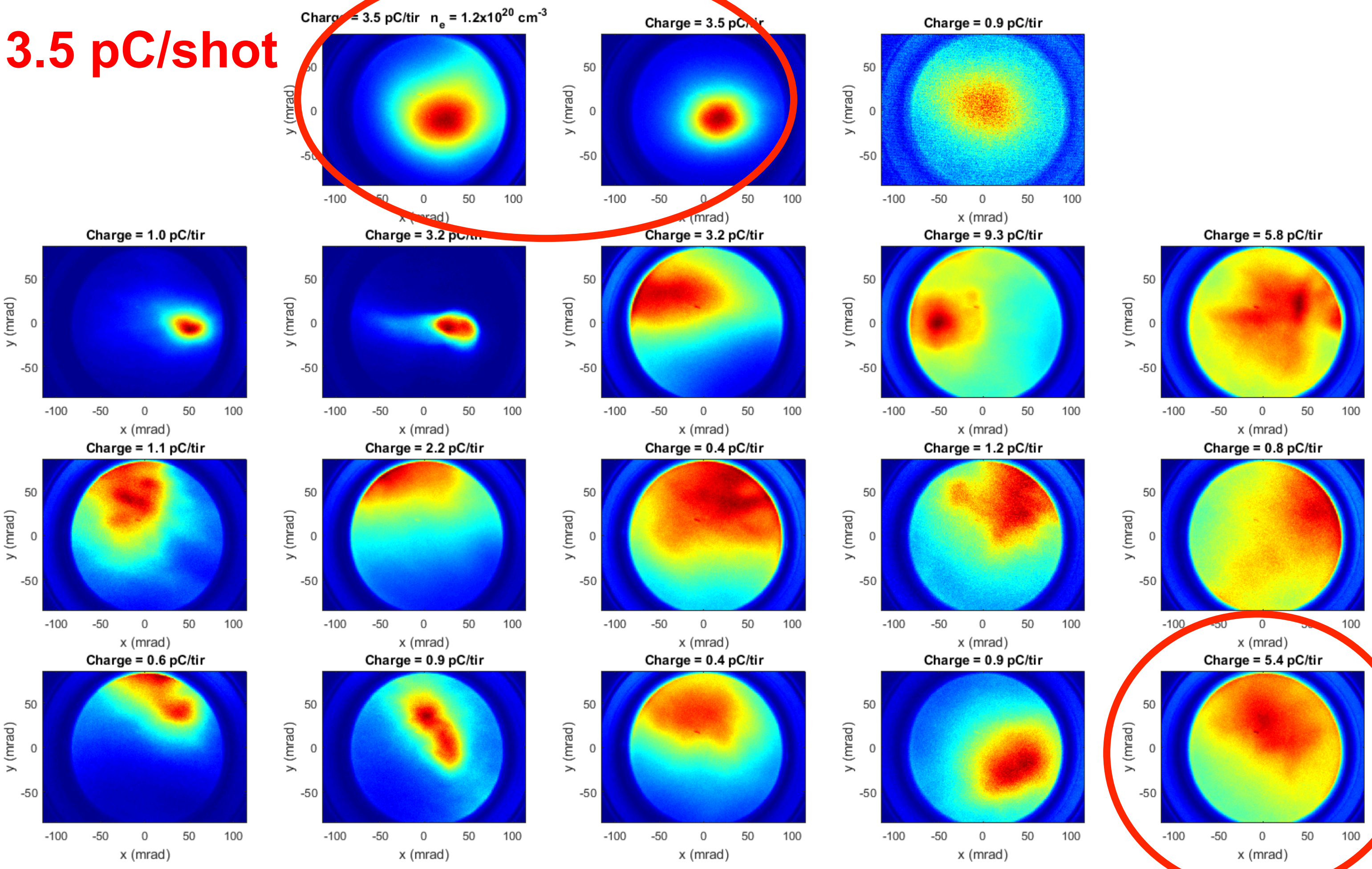
3.4 fs

4 fs

5 fs

10 fs

3.5 pC/shot



5.4 pC/shot

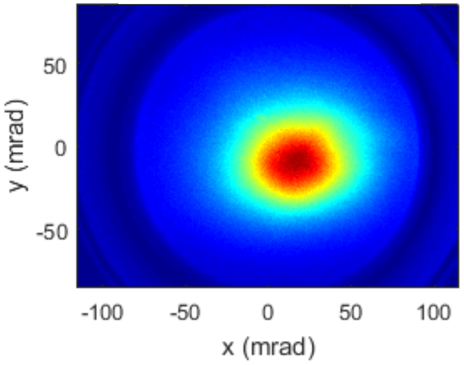
Importance of self-focusing

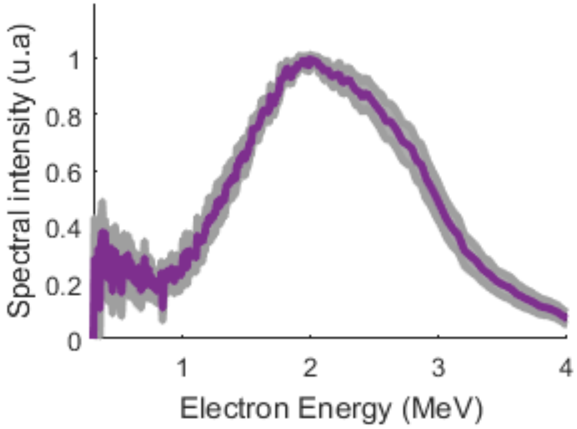
3.4 fs case

$n_e \sim 10^{20}$ cm^{-3}

$P/P_c = 2.5$

3.5 pc/shot



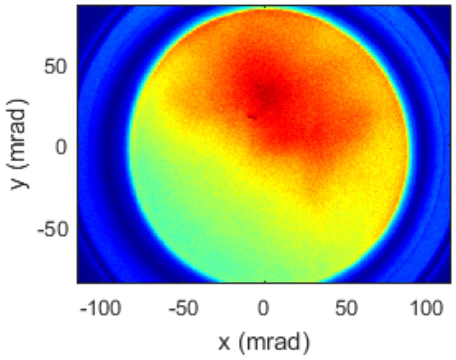


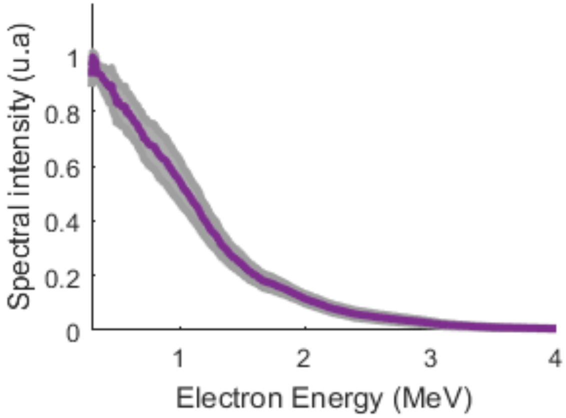
10 fs case

$n_e \sim 3.5\text{x}10^{20}$ cm^{-3}

$P/P_c=3$

5.4 pc/shot





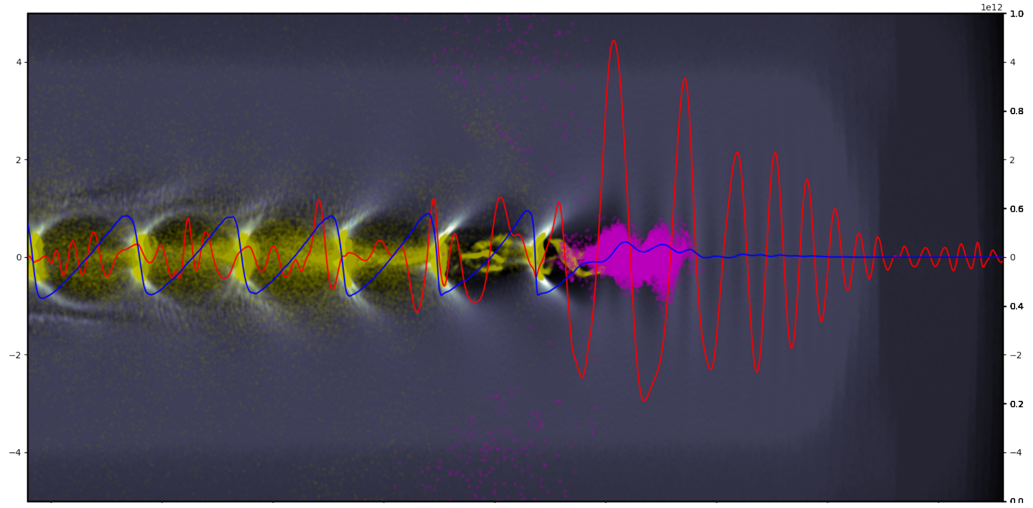
Still possible to obtain MeV beams with longer pulses and higher density but broad distributions (as in Salehi et al., 2017)

PIC simulations (FBPIC, I. Andriyash, Weizmann)

3.4 fs case

$n_e \sim 10^{20}$ cm^{-3}

$P/P_c = 2.5$

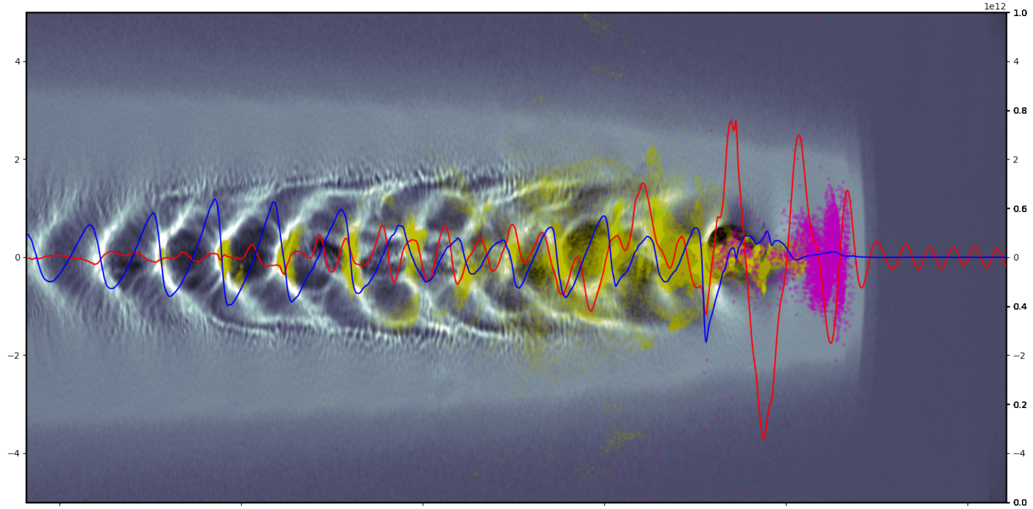


Well defined wake with focusing forces → small divergence

10 fs case

$n_e \sim 3.5\text{x}10^{20}$ cm^{-3}

$P/P_c=3$



Wake structure is destroyed: large divergence

Conclusion

- Single-cycle pulses at the resonance give the best electron beams: routine production of **2-5 MeV at kHz**
- Room for improvement in target design for more stable injection, higher resistance to laser flux…
- New physics at the optical cycle to explore: CEP, dispersion…
- **The scaling laws are also valid in the low energy limit**

Ideal parameters for a robust laser driver for 20 MeV electrons @ kHz repetition rate (e. g. for Compton source):

Laser energy: 20-30 mJ
Optimal duration: 7-8 fs
Optimal plasma density: 6×10^{19} cm^{-3}
Electron energy gain: 20 MeV

Can we do this now ?

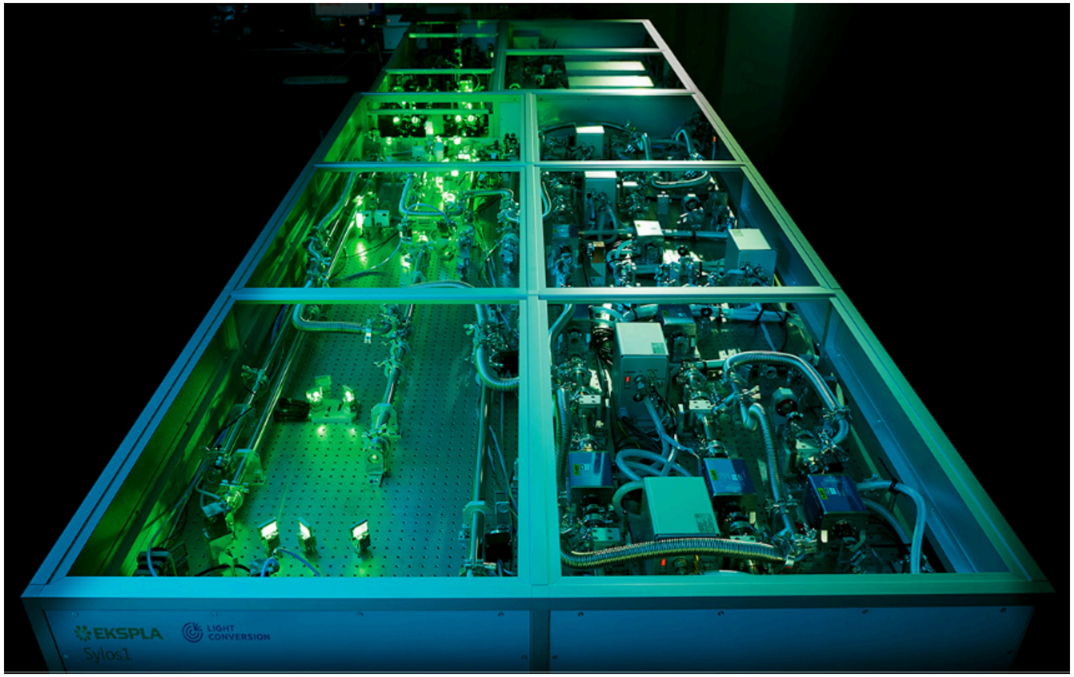
Latest performance of high rep. rate lasers

Ti: sapphire @ **1 kHz**: 40 mJ, 29 fs: Jülich laser (THALES)

A good compromise ? Ti:Sapphire system with >200 mJ, 30 fs @ **100 Hz** available commercially
+ use post-compression for sub-10 fs pulses ?

Latest performance of high rep. rate lasers

OPCPA: 50 mJ, sub-10 fs @ kHz: SYLOS laser, ELI-ALPS



EKSPLA & LIGHT CONVERSION

Ideal on paper, robustness and ease of use for experiments still unknown

→ Large progress in kHz LWFA expected in the next decade

Collaborators

kHz laser-plasma source
L. Rovige, D. Gustas, D. Guénot, A. Vernier
B. Beaurepaire, G. Gallé

PIC simulations:
A. Lifschitz, I. Andriyash (Weizmann)

Laser system:
M. Bocoum, F. Böhle, A. Jullien, J.-P. Rousseau
M. Ouillé, S. Haessler, R. Lopez-Martens

Electron diffraction experiments:
CUOS of University of Michigan:
Z. He, A. Thomas, J. Nees, K. Krushelnick

Sample preparation
S. Scott, M. Lagally, Univ. Wisconsin

Thank you

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